

Have we detected one of the sources responsible for an early reionisation of the Universe?

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ABSTRACT

In a recent paper Pelló et al. have reported a candidate $z = 10$ galaxy, A1835#1916, which was found in a near-infrared survey of the central regions of the gravitational lensing cluster A 1835. If this detection is confirmed and the detection rate turns out to be typical, then the volume averaged ultraviolet emissivity must be rising rapidly with increasing redshift. For a magnification due to gravitational lensing by a factor $\mathcal{M} \gtrsim 25$ estimated by Pelló et al., the inferred star formation rate at $z = 10$ would be about one order of magnitude higher than estimates of the star formation rate density at $z = 6$. Objects at $z = 10$ would contribute substantially to the total source counts at $1.6\mu\text{m}$ and the estimated space density of sources may exceed the space density of dark matter haloes in a ΛCDM model. We therefore argue that if A1835#1916 is indeed at $z = 10$ then either the magnification factor may have been overestimated or the galaxy has a top-heavy initial mass function. Sources with the UV flux and space density of A1835#1916 produce $\sim 33f_{\text{esc}}(\mathcal{M}/25)$ hydrogen ionising photons per hydrogen atom per Hubble time, where f_{esc} is the escape fraction of ionising photons. This rate should be sufficient to reionise most of the diffuse hydrogen in the Universe at redshift ten. We further use a correlation between the equivalent width and the redshift of the Ly α emission line with respect to the systemic redshift observed in Lyman break galaxies to obtain constraints on the ionisation state of the surrounding intergalactic medium (IGM) from the Gunn-Peterson absorption. These constraints also argue in favour of the surrounding IGM being fully ionised. Pelló et al. may thus have detected a population of sources which is responsible for the large electron scattering optical depth indicated by the cross-power spectrum of the temperature and polarisation fluctuations of the cosmic microwave background as measured by WMAP.

Key words: Cosmology: theory – intergalactic medium – large-scale structure of universe – galaxies: formation

1 INTRODUCTION

The unravelling of the reionisation history of the Universe has been the focus of much recent research mainly due to the surprising detection of a large Thompson electron optical depth of $\tau = 0.17 \pm 0.04$ by WMAP (Kogut et al. 2003). If correct, this optical depth requires a substantial ionised fraction of hydrogen at redshift $z = 10 - 20$. This result came somewhat as a surprise as the optical depth for Ly α scattering increases rapidly in the highest redshift QSOs (Fan et al. 2003; Songaila 2004) indicating a drop in the emissivity of hydrogen ionising photons (Miralda-Escudé 2003). This has led to the suggestion that the emissivity of ionising photons peaked at high redshift due to a population of early stars or mini-AGN and that the reionisation may have been

complicated, with an extended epoch of partial reionisation (Madau et al. 2004; Ricotti & Ostriker 2003) and/or the possibility that hydrogen was reionised twice (e.g., Cen 2003; Wyithe & Loeb 2003; Ciardi et al. 2003; Ricotti & Ostriker 2004; Sokasian et al. 2004). The possible detection of a $z = 10$ Ly α emitting star-forming galaxy by Pelló et al. (2004) thus offers exciting prospects to further constrain the reionisation history. This result, if confirmed by further observations, pushes back the epoch when “galaxies” were already shining in Ly α emission by ~ 0.5 Gyr relative to previous detections at $z \simeq 5 - 6$ (Rhoads et al. 2003; Kodaira et al. 2003; Lehnert & Bremer 2003; Hu et al. 2004; Stanway et al. 2004). In this letter, we briefly discuss the implications of detecting such a source for the inferred space density of star-forming

galaxies, for the emissivity of hydrogen ionising photons and the ionisation state of the IGM at $z = 10$. We assume throughout the cosmology to be the concordance Λ cold dark matter model with $(\Omega_\Lambda, \Omega_m, \Omega_b, h) = (0.7, 0.3, 0.04, 0.7)$ and primordial scale-invariant power spectrum ($n_s = 1$) with rms amplitude of the mass fluctuations on scale of $8 h^{-1}$ Mpc, $\sigma_8 = 0.91$.

2 THE $Z = 10$ CANDIDATE GALAXY A1835#1916

2.1 Summary of observations

Pelló et al. (2004, P04) obtained deep ISAAC imaging in JHK of the central 2×2 arcmin² of the gravitational lensing cluster A1835. Together with deep optical imaging in VRI they were able to identify 6 high-redshift ($z > 7$) candidates using the dropout technique (Guhathakurta et al. 1990; Steidel & Hamilton 1992). One of the candidates (#1916) has a redshift estimate from broad-band photometry of $z_{\text{phot}} \approx 9 - 11$ and falls close to the critical line of the cluster for this redshift range. For this candidate P04 obtained a deep J-band spectrum with ISAAC and detected an emission line at $1.33745 \mu\text{m}$ with a flux of $4 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$ and a rest frame width of $\approx 50 \text{ km s}^{-1}$. If interpreted as Ly α emission the redshift of the emission line is $z = 10.00175$. From the location of the source relative to the critical lines of their lensing model, P04 estimate the amplification due to gravitational lensing to be in the range $25 < \mathcal{M} < 100$. The inferred star formation rates (uncorrected for lensing) from the line and continuum fluxes are $4h_{70}^{-2} M_\odot \text{ yr}^{-1}$ and $60h_{70}^{-2} M_\odot \text{ yr}^{-1}$ respectively, using the observed fluxes reported by P04 and the conversions by (Kennicutt 1998). Note that P04 used a different conversion from Ly α flux to star formation rate, obtaining a lower value of the star formation rate.

2.2 The implied space density of star-forming galaxies and star formation rate density at $z=10$

The comoving survey volume per unit redshift is given by

$$\frac{dV_{\text{survey}}(z)}{dz} = \frac{c^3}{\mathcal{M}} \left(\int_0^z \frac{1}{H(z')} dz' \right)^2 \frac{1}{H(z)} d\Omega, \quad (1)$$

where \mathcal{M} is the magnification by gravitational lensing and $d\Omega$ is the solid angle of the area surveyed in the lens plane.

The solid angle in the lens plane with magnification larger than a given value is somewhat uncertain and depends on the lens model. The length of the critical curve in Fig. 1 of P04 is about 180 arcsec. We further assume that for sources within 2.5 arcsec of the critical curve $\mathcal{M} > 25$, then $d\Omega(> \mathcal{M}) \approx 0.25(\mathcal{M}/25)^{-1} \text{ arcmin}^2$ (R. Pello private communication). This is about the same value as Santos et al. (2003) give in their Fig. 7 as average for 9 lensing clusters and assuming that the slits cover about 1/5 of the total magnified area.

Assuming that the survey detects all galaxies in the redshift range $8.5 < z < 10.5$, and that the detection of one galaxy per effective survey volume is representative, the number density of bursting sources with star formation rate

$\text{SFR} \gtrsim 2.4(\mathcal{M}/25)^{-1} h_{70}^{-2} M_\odot \text{ yr}^{-1}$ is given by,

$$n_{\text{burst}} \approx \left(\frac{dV_{\text{survey}}}{dz} \Delta z \right)^{-1} \quad (2)$$

$$\simeq 0.033 \left(\frac{d\Omega_{\text{eff}}}{0.25 \text{ arcmin}^2} \right)^{-1} \left(\frac{\mathcal{M}}{25} \right)^2 h_{70}^3 \text{ Mpc}^{-3},$$

where $d\Omega_{\text{eff}}(\mathcal{M})$ is the effective solid angle in which such a source with magnification factor $> \mathcal{M}$ is typically found. This number is obviously very uncertain as P04 have just found one source and the magnification is also uncertain. However, as we will show later on, despite this large uncertainty the high value of the estimated galaxy space density has interesting implications. Note that the total space density of sources, n_{tot} , including those not currently undergoing a starburst is a factor $10(t_{\text{burst}}/30 \text{ Myr})^{-1}$ larger than that in equation (2). Note also that this would correspond to $3.6 \times 10^5 (d\Omega_{\text{eff}}/0.25)(\mathcal{M}/25)^2$ objects per deg² with H-band AB magnitude of $28.5 + 2.5 \log(\mathcal{M}/25)$ which for magnification factors in the range suggested by P04 approaches the observed number counts at $1.6 \mu\text{m}$ (Yan et al. 1998; Thompson et al. 1999).

Taken at face value, the space density is about a factor $(0.6 - 2)(\mathcal{M}/25)$ times that of Ly α emitters in surveys at redshift 4 to 6 (e.g., Santos et al. 2003). It corresponds to a star formation rate density of $\rho_* \approx 0.08 (d\Omega_{\text{eff}}/0.25 \text{ arcmin}^2)^{-1} (\mathcal{M}/25) h_{70} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$. The total star formation rate is expected to be larger due to the contribution of fainter objects with smaller star formation rates. In Fig. 1 we compare this star formation rate to the compilation of star formation rates at lower redshifts by Bunker et al. (2004). The star formation rate density for our fiducial values is about a factor 4-20 larger than that observed at redshift six (Bouwens et al. 2004; Bunker et al. 2004). We also show the inferred star formation rate density assuming $\mathcal{M} = 5$ and a top-heavy initial mass function (IMF) (middle and lower point on the error bar respectively). If A1835#1916 is indeed at $z = 10$, $\mathcal{M} = 25$ and the average volume that contains such a source is not underestimated the ultraviolet emission rate density would have to increase rather rapidly. Such a rapid rise of the emissivity towards larger redshift may explain why the detected source has not been found closer to the lower end of the redshift range where it could have been detected ($z \sim 7 - 8$), as it is most likely in a flux-limited sample. A continuation of the decrease of the comoving star formation rate density between $z = 4$ and $z = 6$ suggested by Bunker et al. (2004) would only be possible if the magnification factor and/or the space density of the sources have been overestimated, or if the IMF at $z \sim 10$ becomes top-heavy.

2.3 The space density of galaxies and DM haloes at $z=10$

As discussed in the last section the inferred space density of sources and star formation rate density are quite large for a Salpeter IMF if the magnification $25 < \mathcal{M} < 100$ derived by P04 from the location of the source relative to the critical lines of their lens model is correct.

To investigate this further we show in Fig. 2 the expected space density of dark matter haloes in the concordance ΛCDM model at redshift $z = 10$ (thick solid curve).

In order to compare that to the space density of the

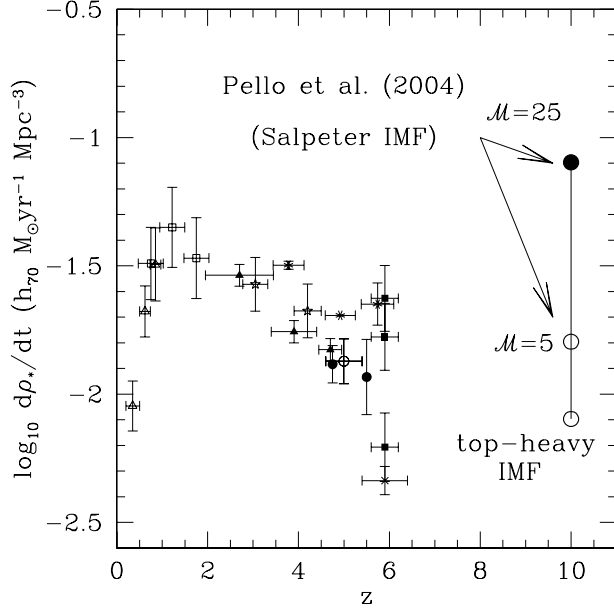


Figure 1. The star formation rate density as a function of redshift adopted from Bunker et al. (2004). The data is from Lilly et al. (1996) (open triangles), Connolly et al. (1997) (open squares), Steidel et al. (1999) (stars), Iwata et al. (2003) (open circles), Bouwens et al. (2003) (solid triangles), Bouwens et al. (2003) (solid squares), Fontana et al. (2003) (solid circles), Giavalisco et al. (2004) (asterisks), Bunker et al. (2004) (crosses). The value inferred from Pelló et al. (assuming a Salpeter IMF) is shown as a solid circle for our fiducial values of the magnification ($\mathcal{M} = 25$) and the estimated volume of the survey. The point in the middle of the error bar (open circle) is obtained assuming five times smaller magnification of the source and the point at the end of the error bar assuming a top-heavy IMF.

observed source(s) we have to assume a duration of the burst, a star formation efficiency and an IMF. The total number of haloes required to host the bursts is $n_{\text{tot}} \simeq 0.32(t_{\text{burst}}/30 \text{ Myr})^{-1} (\Omega_{\text{eff}}/0.25 \text{ arcmin}^2) (\mathcal{M}/25)^2 h_{70}^3 \text{ Mpc}^{-3}$.

We will start by assuming that all baryons in a DM halo turn into stars (*i.e.*, we assume a star formation efficiency $f_* = 100\%$) on a time scale t_{burst} so that $\dot{M}_* = 0.14 M_{\text{dm}}/t_{\text{burst}}$. This gives a (lower limit of the) mass of the dark matter halo hosting A1835#1916 of $M_{\text{dm}} \gtrsim 4.2 \times 10^8 (t_{\text{burst}}/30 \text{ Myr}) (25/\mathcal{M}) M_{\odot}$, if we assume a Salpeter IMF. For a top-heavy IMF the inferred mass would be a factor up to ten smaller. Note that the galaxy mass function is expected to have shallower slope at small masses when feedback effects are included.

The hatched regions show the resulting lower limits of space density for a range of magnifications from 5 – 100 as indicated on the figure. The arrows show how these limits would change if the burst duration is increased by a factor ten or the assumed typical volume hosting such a source has been underestimated by a factor of ten. Independent of our detailed assumptions, sources with such a high space density must be hosted in rather shallow potential wells with virial velocities $v_{\text{vir}} \lesssim 50 \text{ km s}^{-1}$ which fits in well with the narrow width of the Ly α emission line. The star formation efficiency in shallow potential wells ($M_{\text{dm}} < 10^7 - 10^8 M_{\odot}$) is, however, expected

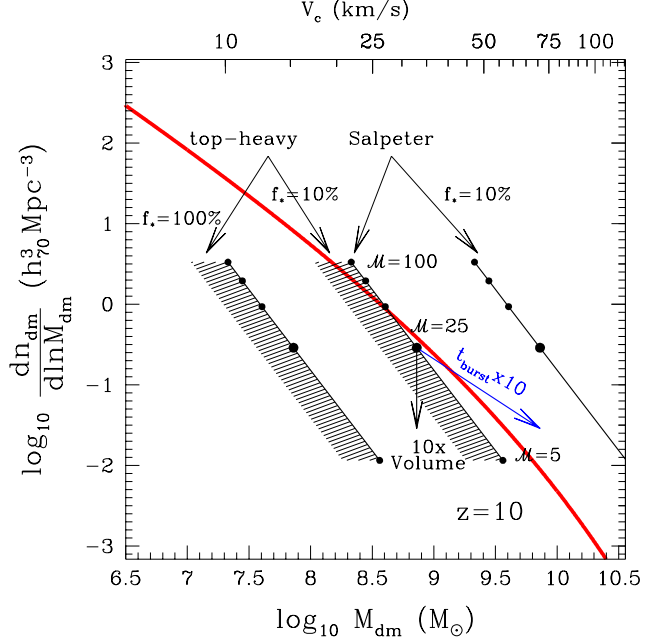


Figure 2. The solid curves shows the mass function of dark matter haloes at $z = 10$ for a Λ CDM concordance model. The hatched regions show lower limits for the total space density of haloes hosting sources like A1835#1916 for a range of magnification and two different IMF. We have assumed that 100% or 10% (as indicated by the labels) of all available baryons turn into stars within $t_{\text{burst}} = 30 \text{ Myr}$. The arrows show how the limits change with increased duration of the burst and increased typical volume in which a source like A1835#1916 can be found.

to be of order 10% (*e.g.*, Ricotti et al. 2002). The corresponding increase of the estimates for the halo masses is also shown in Fig. 2.

For a Salpeter IMF and 10% star formation efficiency our estimated space density substantially exceeds the simple Λ CDM prediction. However, for a top-heavy IMF both the assumed star formation efficiencies agree with the model. If our assumed estimates of the space density and/or the magnification factor are somewhat too large, then even assuming a shallower galaxy mass function (expected if feedback effects are important) would still agree with the Λ CDM prediction and with a star formation efficiency as low as 10%. As discussed above the space density is obviously very uncertain and a more moderate amplification of say $\mathcal{M} \sim 5$ may actually not be implausible given that there will be uncertainties in the model of the gravitational lens and the assumed cosmological model. The shallower slope of the galaxy mass with respect to the halo mass function that is expected when feedback effects are included also suggests that a large magnification is unlikely.

3 THE IONISATION STATE OF HYDROGEN AT $Z=10$

The observed candidate galaxy at $z = 10$ offers two routes to constraining the ionisation state of hydrogen in the IGM. With the star formation density from section 2.2 we can estimate the total ionising emissivity, while the observed Ly α emission line and its equivalent width can constrain the Gunn-Peterson optical depth. We now discuss each of these constraints in turn.

3.1 The ionising emissivity

For a Salpeter IMF ~ 4000 ionising photons are produced per hydrogen atom in the matter turning into stars (*e.g.* Haiman 2002). The emissivity of hydrogen ionising photons per hydrogen atom per Hubble time, t_H , is then $t_H d(n_\gamma/n_H)/dt \sim 33h_{70}f_{\text{esc}}(d\Omega_{\text{eff}}/0.25\text{arcmin}^2)^{-1}(\mathcal{M}/25)$, where f_{esc} is the escape fraction of ionising photons. Recall that this is only the contribution from objects bright enough to be detected. Note also that for population III stars the emissivity could be larger by a factor up to two (*e.g.*, Tumlinson & Shull 2000; Bromm et al. 2001).

It is somewhat uncertain how many photons are needed to actually reionise the Universe and estimates vary from a total of a few to a few tens of photons per hydrogen atom (Madau et al. 1999; Miralda-Escudé et al. 2000; Haiman et al. 2001). For a magnification of $\mathcal{M} = 25$ the emissivity of ionising photons should be sufficient to fully reionise hydrogen.

3.2 Suppression of the Ly α emission due to Gunn-Peterson absorption

The line profile appears not to show the characteristic asymmetry due absorption by the surrounding IGM/ISM seen in typical high-redshift Lyman- α emitters. However, considering the very low S/N this is probably not a reason for concern. The P04 estimate for the star formation rate based on the Ly α emission is a factor 15 smaller than that based on the UV continuum emission, suggesting that Ly α is strongly absorbed either by absorption intrinsic to the source or due to the Ly α opacity of the IGM in front of the source (Miralda-Escudé 1998), or both. We can therefore write the observed Ly α emission as $I_{\text{obs}} = T_w T_{\text{IGM}} I_{\text{em}}$ where T_w and T_{IGM} are the transmission factors for absorption by the IGM and intrinsic absorption, respectively, and $T_w T_{\text{IGM}} \approx 0.067$. The transmission of the IGM is related to the optical depth of the red wing of the Ly α absorption trough produced by the IGM in front of the source as $T_{\text{IGM}} = 1 - \exp(-\tau_{\text{IGM}})$. The IGM optical depth τ_{IGM} will depend on the (comoving) radius R_S of the Strömgren sphere in which the source is embedded and the peculiar velocity of the emitting gas Δv_w with respect of the Hubble flow (Haiman 2002; Santos 2003). The emitting gas then has a redshift $\Delta v = H(z)R_S/11 + \Delta v_w$ relative to the absorbing gas just outside the Strömgren sphere, where $H(z)$ is the Hubble constant. If we further assume that the absorbing IGM outside the Strömgren sphere has no peculiar velocity relative to the Hubble flow, the opacity is given by

$$\tau_{\text{IGM}}(\Delta v) = c \int_{10-\Delta z}^{10} n_{\text{HI}}(z) \sigma_{\text{Ly}\alpha}(\Delta v) \frac{dz}{dz},$$

where $\sigma_{\text{Ly}\alpha}$ is the cross section for Ly α absorption and n_{HI} is the number density of neutral hydrogen. The integral converges for $\Delta z \gtrsim 1$. We do not know the relative contribution of intrinsic and IGM absorption to the total transmission. In Fig. 3 we therefore show the upper limit on the mean (mass weighted) neutral fraction, $\langle x_{\text{HI}} \rangle_M$, of the IGM as a function of Δv for a range of values of the intrinsic transmission T_w .

As expected for small values of Δv , *i.e.*, a small R_S and a small Δv_w , the surrounding IGM would have to be fully ionised. Otherwise the Ly α emission would be completely absorbed by the red wing of the Gunn-Peterson trough. If there was no intrinsic absorption (*i.e.*, $T_w = 1$, $T_{\text{IGM}} = 0.067$) a

$\Delta v[\equiv H(z=10)R_S/11 + \Delta v_w] = 650 \text{ km s}^{-1}$ would be required to be consistent with a fully neutral surrounding IGM.

The constraints on the neutral state become considerably stronger if we allow for a significant fraction of the absorption to be intrinsic. If the intrinsic absorption is 90%, (*i.e.*, $T_w = 0.1$, $T_{\text{IGM}} = 0.67$) the neutral fraction of the IGM would have to be smaller than 20% for values of Δv as large as 1000 km s^{-1} . It would thus help greatly if we could put some constraint on range of plausible values of T_w .

An approximate estimate can be obtained from studies of Lyman break galaxies (LBGs) at redshift $z = 3 - 4$ (*e.g.*, Shapley et al. 2003). LBGs show Ly α either in absorption or emission. For LBGs with Ly α emission, there is a wide range of equivalent widths and the centre of the Ly α emission line is generally redshifted by $\approx 200 - 300 \text{ km s}^{-1}$ relative to the stellar absorption lines and nebular emission lines which presumably are at the systemic redshift of the galaxy (Shapley et al. 2003). This systematic offset is generally taken as evidence for galactic winds and the Ly α emission is believed to come from outflowing matter on the far side of the galaxy. Interestingly, Shapley et al. (2003) find a correlation between the equivalent width (EW) of the Ly α line and its velocity shift, which we have reproduced in Fig. 4. The unabsorbed equivalent width (EW_0) is determined by the age, IMF and metallicity of the stellar population producing it. Typical values are in the range $\text{EW}_0 = 240 - 350 \text{ \AA}$ for Population II stars and $\text{EW}_0 = 400 - 850 \text{ \AA}$ for Population III stars (Schaerer 2003). If the line is absorbed by local gas and by the the wind, the EW will be reduced by a factor T_w . The measured Ly α equivalent widths at $z \sim 3$ should thus be a good proxy for the intrinsic transmission of LBGs. If the profile of the unabsorbed Ly α line is a Gaussian with $\sigma_w = 300 \text{ km s}^{-1}$ and part of the blue wing of the line is absorbed by a galactic wind, it should be possible to approximate the correlation by $T_w = \text{Erfc}(\Delta v_w/\sigma_w)$, where $\text{Erfc}(x)$ is the complementary error function and $T_w = \text{EW}/\text{EW}_0$. We indeed obtain a reasonable fit shown as the solid and dashed curve in Fig. 4 with $\text{EW}_0 = (300 \pm 100) \text{ \AA}$ (Schaerer 2003), and a small offset of 13% of T_w .

If we assume that the inferred correlation between intrinsic transmission and redshift of the emitting gas relative to the systemic redshift found at $z \sim 3$ for LBGs also holds for A1835#1916, we can specify the intrinsic transmission for a fixed size of the Strömgren sphere. The thick solid curves in Fig. 3 show these significantly tighter constraints for a range of radii of the Strömgren sphere. We have thereby assumed a wind velocity $\sigma_w = 300 \text{ km s}^{-1}$, but the upper limits do not change if we assume $\sigma_w = 100 \text{ km s}^{-1}$ which may be more appropriate for sources hosted in shallow potential wells as is likely for A1835#1916. The curves also depend only very weakly on the assumed extrapolation of the correlation of T_w with Δv_w towards small velocities. For $R_S \lesssim 5 \text{ Mpc}$ (comoving) the surrounding IGM must be at least partially ionised to be consistent with the observed Ly α emission if the $T_w - \Delta v_w$ correlation of LBGs holds for A1835#1916.

4 DISCUSSION AND CONCLUSIONS

The implications of the possible detection of a redshift 10 galaxy by Pelló et al. (2004) depend crucially on the assumed magnification factor and on the assumption that the detection

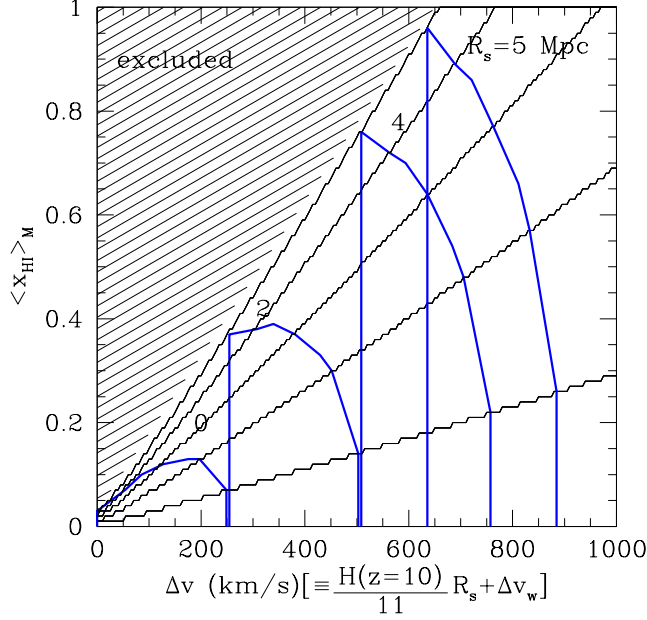


Figure 3. The thin solid curves show upper limits on the (mass-weighted) neutral fraction of hydrogen as a function of the redshift $\Delta v = H(z)R_S/11 + \Delta v_w$ relative to the absorbing gas just outside the Strömgren sphere, where $H(z)$ is the Hubble constant, R_S is the (comoving) radius of the Strömgren sphere in which the source is embedded and Δv_w is the peculiar velocity of the emitting gas with respect of the Hubble flow. The limits were calculated assuming that the absorption of the Ly α emission inferred from the equivalent width of the Ly α line is due to combined absorption of the surrounding IGM and some intrinsic absorption by the ISM, galactic winds and gas inside the Strömgren sphere surrounding the source. The thin solid curves are for transmission factors due to intrinsic absorption of $T_w = 100, 67, 42, 22$, and 10%, respectively (top to bottom). The thick solid curves show the upper limits of the neutral hydrogen fraction assuming that the source is at the centre of a Strömgren sphere of comoving radius $R_S = 0, 2, 4$, and 5 Mpc (from left to right) assuming the correlation of T_w with Δv_w shown in Fig. 4.

of one source of this kind in the effective survey volume is representative. Our estimate of the space density is consistent with the predicted number densities of DM haloes in a LCDM model. For a Salpeter IMF, it requires, however, a rather extreme (close to 100%) star formation efficiency. For a “top-heavy” IMF a star formation efficiency $\geq 10\%$ would be sufficient. If stellar feedback is important in these objects then the slope of their mass function is expected to be shallower than the mass function of DM haloes in a Λ CDM model. A somewhat smaller magnification and/or space density would then be required to be consistent with the model prediction. It seems thus worthwhile to investigate if a smaller magnification is consistent with the uncertainties in the model of the gravitational lens and the assumed cosmological model. If the magnification was indeed smaller, then the location of the yet missing counter-image would also be much less well constrained. More objects of this kind are clearly needed for a more solid assessment of their space density and the implied emissivity. A large star formation rate density and a moderate amplification factor of this source would obviously be good news for ongoing surveys for objects at $z > 7$, both behind lensing clusters and in the field. For the fiducial magnification

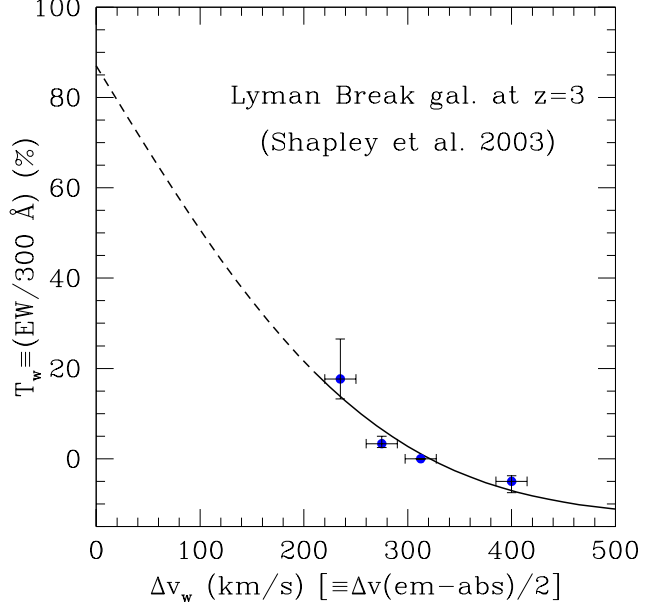


Figure 4. Observed correlation between the Ly α equivalent width, and thus the transmission factor, with the velocity shift of the Ly α emission line with respect to the rest frame velocity of the galaxy. The solid curve shows a fit, motivated in the text. The dashed line shows the extrapolation to small Δv_w . Note that the upper limits on $\langle x_{\text{HI}} \rangle_M$ in Fig. 3 are not sensitive to the particular choice of the extrapolation and the assumed typical wind velocity σ_w .

$\mathcal{M} \sim 25$ and assuming Salpeter IMF, the evolution of the star formation rate density would show a very rapid decrease between $z = 10$ and $z = 6$ followed by a increase between $z = 6$ and $z = 4$ which would suggest that A1835#1916 is part of a separate population of objects. This raises the question what could have led to the rapid decline of such a population. A number of authors have made the suggestion that negative feedback due to star formation in shallow potential wells could lead to a rapid decline of a first generation of star-forming objects (e.g., Efstathiou 1992; Barkana & Loeb 2000; Ricotti 2002). If instead the IMF becomes top-heavy at $z \gtrsim 10$, then the star formation rate density is consistent with the decreasing values observed between $z = 4$ and $z = 6$. For the fiducial magnification $\mathcal{M} \sim 25$ the emissivity of hydrogen ionising photons emissivity is large enough that the post-overlap state of the reionisation process should have been reached and the neutral fraction of hydrogen should be small. Sources like A1835#1916 may thus well be responsible for the large electron scattering optical depth measured by WMAP. If the magnification is $\mathcal{M} \sim 5$ and/or the space density is overestimated the star formation rate density at $z = 10$ could be consistent with a smooth continuation of the observed evolution at lower redshift. These sources, however, would not be sufficient to reionise at $z = 10$ and the low neutral fraction inferred by the detection of the Lyman- α line would have to be explained in another way, for instance by a fainter population of galaxies or by partial ionisation by X-rays produced by accretion onto intermediate mass black holes in mini-AGNs (Madau et al. 2004; Ricotti & Ostriker 2003).

The observed Ly α flux gives independent constraints on the ionisation state of the surrounding IGM. If the surround-

ing IGM were not ionised, the strength of the line requires that its centre is redshifted by 650 km s^{-1} with respect to the velocity of the neutral IGM. This could occur due to the absorption and resonant scattering of the $\text{Ly}\alpha$ photons by a galactic wind, but such a large offset appears unlikely considering the rather shallow potential well that may host this galaxy. The constraints tighten further if the observed correlation between transmission and velocity shift of $\text{Ly}\alpha$ emission in LBGs also holds for A1835#1916. In this case the minimum size of the ionised region consistent with a neutral surrounding IGM is $R_S \sim 5 \text{ Mpc}$ (comoving), independent of the velocity shift.

We agree with Loeb et al. (2004) that the source itself is unlikely to ionise such a large region on its own. However, the large emissivity of ionising photons which is implied by the small effective survey volume, if confirmed, would make the lack of a suppression of the $\text{Ly}\alpha$ emission due to the Gunn-Peterson absorption by the surrounding IGM less surprising. Clearly, a small neutral fraction at $z = 10$ in the diffuse IGM would be further good news for surveys of high-redshift objects which would strongly benefit from $\text{Ly}\alpha$ emitters with large equivalent widths. A space density as large as inferred here would also mean that a significant fraction of the faintest objects detected at $1.6 \mu\text{m}$ may be at $z \sim 10$.

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